Impacts of future biological-technological progress on arable farming*

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Summary

This article deals with biological-technological developments in crop production and their impacts on arable farming within the next 20 years. Possible future technological developments are evaluated with the help of a Delphi survey. The impacts of promising new technologies are estimated by means of a Linear Programming model under three different scenarios.

An important outcome of the model calculations is that crop production is strongly influenced by the economic and political environment. The most promising improvements are offered by new technologies which enhance labour productivity. Competitive new technologies can cause unbalanced crop rotations with non-desirable ecological effects and substantial changes in agricultural commodity markets.

Keywords: technology assessment, plant production, biotechnology, Delphi survey, Linear Programming.

1. Introduction

By means of an international expert investigation, future biological-technological developments in arable farming were assessed by the authors (Gotsch and Rieder, 1989, 1990). With the help of the so-called Delphi method this study provides information on future developments which will be available for Swiss farmers in the long-term (20 to 30 years) and distinguishes them from developments possibly available within the next 10 to 15 years (hereafter referred to as the medium-term).

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In a next step, medium-term impacts of promising new technologies on optimal land use and production intensity in arable farming were obtained by means of a Linear Programming model (LP model) under three different economic scenarios. The connections between the results of the Delphi survey, the scenarios and the LP model are shown in Figure 1. Some of these results are presented in this paper.

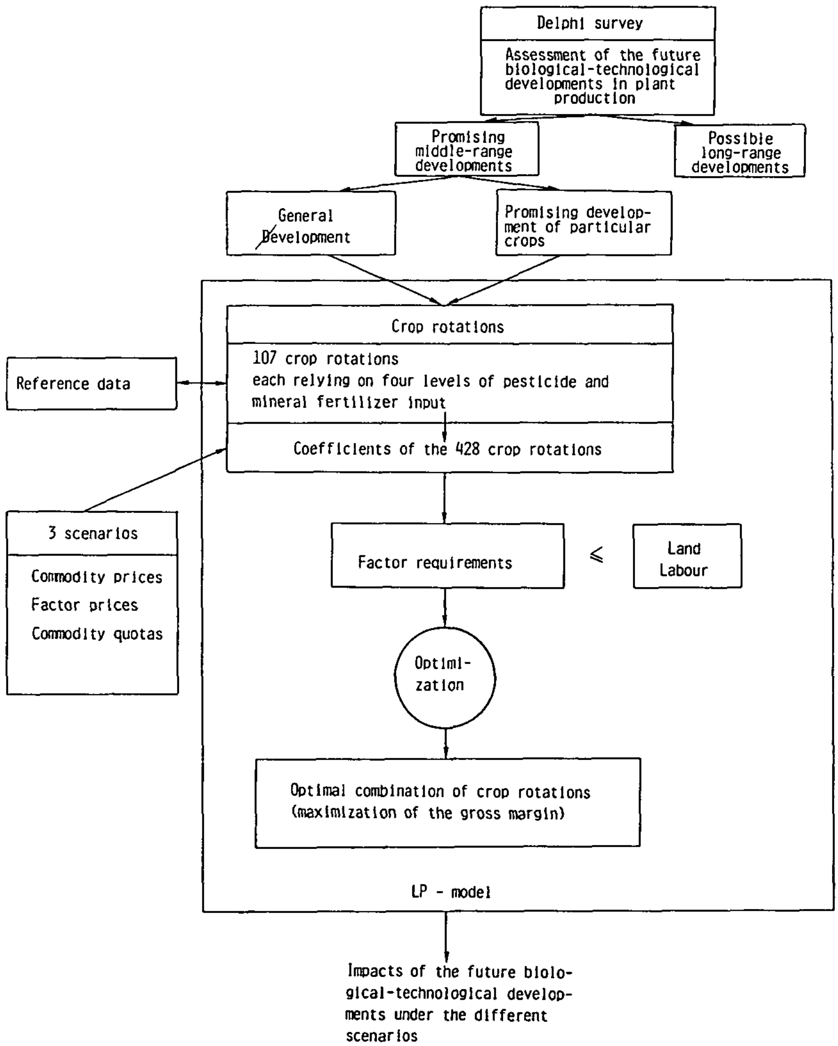

Figure 1. *Connection between Delphi survey, scenarios and LP model*

2. Forecasting future biological-technological progress

2.1. *Methodology*

For any long-range prognosis it is necessary to take into account discontinuity, which can be caused by innovations over time. For this purpose intuitive methods such as the Delphi method are suitable (Mohn, 1974).

The following special qualities characterize the Delphi procedure:

- Use of a formal questionnaire,
- Anonymous personal answers,
- Determination of a statistical group answer,
- Information to the participants,
- Repetition of the investigation.

Some of the questions of the Delphi survey discussed in this article were formulated as assumptions. For every assumption an answering expert had to estimate the chance of its realization by the year 1997 and 2007. For the other questions an estimation of the future development of certain characteristic values (e.g., relative costs of developing new plant protection products) was requested. In addition we tried to obtain forecasts for the practical adoption of progress at the farm level.

In a second investigation the experts' task was to examine the previous answers with the help of the statistical group values (median and quartiles) evaluated from the first investigation.

Sackman (1974) (in Farrell et al., 1984) has reservations concerning the Delphi method. He perceives a danger in giving too much weight to the opinions of experts. The author names this phenomenon an 'experts' halo'. He equally fears that experts could have their own material interest in the success of a technology and therefore give too optimistic a forecast of its prospects. But Martino (1972) shows, with the help of other authors' studies, that the results of a Delphi study have good repeatability. He found that, with a representative group of experts for a certain field, it is improbable that another equally representative group of the same size will make a forecast at the same time which is essentially different from that of the first one.

2.2. *Results*

Concerning the LP model, the results of the Delphi survey were integrated in the following way:

1. The assessment of future biological-technological progress in crop production in fields currently exclusively in the state of basic research requires long-range considerations of about 30 years. This is the case for most of the important future applications of genetic engineering for crop production, such as the transfer of nitrogen fixation genes from legumes to

non-legumes or the improvement of photosynthetic efficiency by means of genetic engineering. Their impacts on practical farming in the long-term are difficult to forecast. They depend strongly on future research policy and the economic, legal and social influences which promote or impede research in specific fields. This is especially relevant for private research. Moreover, sudden breakthroughs or unexpected difficulties can drastically accelerate or retard progress.

2. In the middle-term (10 to 15 years) biological-technological progress can be expected which will allow a continuous increase in yield *potential*. The result of such research already in progress is less affected by current economic, social and political decisions due to the long time horizon of biological-technological progress in crop production (e.g., new crop varieties which will be used by the farmer within the next 10 years are already being bred today). For this reason, we assume that the average yield increase of the last 30 years for Switzerland can be extrapolated linearly for the next 15 years, the actual intensity of pesticide and fertilizer input supposed.
3. Based on this assumption of linear yield increases, it was found that particular progress can be expected in fields where basic research has advanced today (see Section 5.3.1).
4. The middle-term exploitation of the yield potential and the application of the new technologies described above depend on the economic and political environment. Therefore, with the help of a Linear Programming model, we define three scenarios under which we determine optimal crop production and the impact of new technologies.

3. Scenarios

The impacts of different technological developments on optimal land use are assessed under three scenarios with a time horizon of 15 years (up to the year 2003). The scenario 'Going On' is the reference scenario with actual Swiss input and commodity prices. Labour costs amount to 16sFr./h for occasional labour. This corresponds to wages paid in the period 1985–1987 in Switzerland for this purpose. In the long term, permanent labour is mobile and therefore scenario-dependent opportunity costs are taken into account on an annual basis. They amount to sFr. 20,000 in the scenario 'Going On', which is less than the market price for hired labour. This allows a differentiation between marginal costs of family labour and the market price of labour. In the scenario 'More Ecology', prices for mineral nitrogen fertilizer and pesticides are increased three times in comparison to the scenario 'Going On'. Costs for permanent and occasional labour are reduced by about 40% compared to the reference scenario, and occasional labour is more readily available. The scenario 'Liberal Market' represents a situation of prospering economy with labour costs increased by 50% compared to the reference scenario. Occasional labour is restricted. Commodity and input prices are at the 1990 level of the European Community. Compared to the scenario 'Going On', the ratio between commodity prices and those for mineral fertilizer and pesticides is reduced.

4. Structure of the LP model

Promising future developments, which we identified in our Delphi survey, are linked to seed. In contrast to other technological progress, such as new mechanical developments, biological-technological progress in the form of seed is a very mobile production factor. Its adoption causes little economic risk. Therefore, after a short period, economically competitive new plant varieties can be expected to be cultivated by farms of all size and type. An example can be seen in Switzerland's principal wheat variety of the last decade; it gained a proportion of about 70% of total Swiss wheat area within only six years and is cultivated by all farm types in all Swiss arable regions.

Taking into account these special qualities of biological-technological progress in the field of plant production, we develop a crop rotation model instead of an optimization model with different farm types. In this model, the costs of labour represent both, the opportunity costs of labour (determined by, for instance, the mobility of labour) and the marginal product of labour input in animal production or other activities on farm level. The effects of biological-technological progress under different economic or market conditions are tested in different special scenarios (see Section 5.3.5 and Gotsch, 1990: 112).

This type of model allows for the building up of important agronomic relations and is transparent and effective enough to analyse new technologies. During the optimization process, the model chooses between 107 fixed crop rotations. A crop rotation is defined as a temporal sequence of crops (e.g., a cereal intensive rotation such as spring oats – winter wheat – spring barley – winter wheat – winter barley; a root crop intensive rotation such as potato – sugar beet – soybean; or an agronomically well-balanced rotation such as potato – winter wheat –winter rye – soybean). The proportion of a crop in the whole rotation and its position within the rotation has an effect on its yield.

The model used in this study embraces the following 12 crops: winter wheat, winter and spring barley, winter rye, spring oats, grain maize, rape seed, potato, sugar beet, faba bean, soybean and sown grass-clover meadow.

For each crop rotation, four different combinations of pesticide application and fertilization exist:

a) with pesticides and mineral fertilization exclusively;
b) with pesticides and mixed mineral/organic fertilization;

c) without pesticides and with mixed mineral/organic fertilization;
d) with exclusively organic fertilization and without pesticides.

For every hectare of a crop rotation, an average factor input (seed, mineral fertilizer, pesticides, machine costs, permanent and occasional labour divided into six periods) produces a certain product output. All the products are sold. Machines are hired. Commodity and factor prices depend on the scenario (see Section 3). The result of the optimization is a combination of different crop rotations with boundary conditions imposed by land and labour resources.

The model represents a situation with good arable land and favourable climate. Therefore the area available in the model is limited to 100,000 ha which corresponds to about one third of the actual Swiss crop area. Our model has also taken into account the impact of technological progress on a region with mixed arable/animal farming: allowance has been made for labour on an additional 20,000 ha of natural meadow without contributing to the economic result in the objective function. This represents a situation in which farmers have to assign a certain amount of labour for the animal sector. Results of these calculations are presented in Gotsch (1990).

Analysing the impacts of biological-technological progress on different regions with different natural production conditions (such as climate and soil quality) was not possible due to a lack of empirical data (for example the effects of different agronomic measures such as chemical plant protection, mineral fertilization and various crop rotations on yield).

5. Results of the LP model

5.1. *Reference solution*

First we test the model with reference data (see Figure 1). The upper part of Table 1 shows the optimal crop rotation combination with average Swiss yields for the years 1985–1987. The whole area available in the model is cultivated with three crop rotations. Pesticides are applied combined with mixed organic/mineral fertilization. The crop rotation with sugar beet is restricted by the sugar beet quota available. The remaining area is divided up between a crop rotation with potato and one with an important fraction of sown meadow.

The lower part of Table 1 presents a comparison of the relative proportions of the model crops. It corresponds to the actual statistical situation in the region of Switzerland's highest quality arable land in 1990 (Bundesamt für Statistik, 1991). Earlier statistical data for this region do not exist. Table 1 shows our model to be an acceptable representation of reality. The considerably higher proportion of grain maize and the lower proportion of winter wheat in the model region require further explanation: in the model calcula-

Table 1. *Optimal crop rotations and areas of the crops in the model region, with average Swiss yields for the years 1985–1987 and in the Swiss arable region, 1990*

Optimal combination of crop rotations with yields 1985–1987						Fertilization	Chemical crop protection	Proportion of total area (%)
SU	WW	WB	GM			Mixed	Yes	41
GM	GM	WW	SM	SM	SM	Mixed	Yes	30
PO	WW	WB	RS			Mixed	Yes	29

Crop	Area of the crops in the model region with yields 1985–1987 (rel. proportion)	Area of the crops in the Swiss arable region 1990 (rel. proportion)
WW	22.53	34.68
WB	17.60	12.76
SB	0	0.82
WR	0	1.02
OA	0	2.40
GM	20.26	9.69
PO	7.21	6.57
SU	10.39	7.00
RS	7.21	6.41
SO	0	0.47
FB	0	0.06
SM	14.80	18.11
Total	100.00	100.00

FB: faba bean; GM: grain maize; OA: spring oats; PO: potato; RS: rape seed; SB: spring barley; SM: sown meadow; SO: soybean, SU: sugar beet; WB: winter barley: WR: winter rye; WW: winter wheat.

tions, the price for grain maize was sFr. 4/dt (5.5%) higher than the guaranteed price that farmers obtained in 1990. Sensitivity analysis of the model shows that a reduction in price of this extent causes a reduction in grain maize area to about half of that of the reference solution presented in Table 1, i.e., 10% (Gotsch, 1990). The higher proportion of winter wheat area in reality is explained by the reduction in the prices of grains for feeding in 1990 compared to the prices used in the model calculations.

5.2. *Linear extrapolation of yields*

Table 2 represents the optimal combination of crop rotations with yields linearly extrapolated to the year 2003 under the three scenarios described in Section 3. In all three solutions, the whole area available is cultivated. In the scenario 'Going On', the same production method (mixed organic/mineral fertilization and chemical crop protection) is optimal. Concerning the crop rotations, changes in the sugar beet and the potato crop rotation

Table 2. *Model results with linear extrapolation of average Swiss crop yields*

Scenario	Optimal combination of crop rotations						Fertilization	Chemical crop protection	Proportion of total area (%)
'Liberal Market'	GM	WW	RS	SM	SM	SM	Organic	No	59
	SU	WW	WR	FB			Mixed	No	34
	SO	WW	FB	WR			Mixed	Yes	7
'Going On'	GM	GM	WW	SM	SM	SM	Mixed	Yes	37
	SU	WW	WR	GM			Mixed	Yes	36
	PO	WW	WR	GM			Mixed	Yes	27
'More Ecology'	PO	WW	WR	RS			Mixed	No	34
	SU	SO	WW	PO	WB	WR	Mixed	No	27
	GM	GM	WW	SM	SM	SM	Organic	No	21
	SU	WW	WR	GM			Organic	No	18

FB: faba bean; GM: grain maize; PO: potato; RS: rape seed; SM: sown meadow; SO: soybean; SU: sugar beet; WB: winter barley; WR: winter rye; WW: winter wheat.

can be noted. Winter rye is produced in place of winter barley. This change can be explained by the similar qualities of winter barley and winter rye which cause the model to be very sensitive to slight variations in the coefficients of these crops. In addition, the constant sugar beet quota reduces the area of the crop rotation with sugar beet due to the yield increase of this crop. This reduction is compensated by the crop rotation with grain maize and sown meadow. The crop rotation with potato is slightly reduced and in place of rape seed grain maize is grown, due to the relatively stronger increase in the yield of grain maize compared with rape seed.

Compared to the scenario 'Going On', the high labour costs and low commodity prices of the scenario 'Liberal Market' make crop rotations with greater labour productivity more competitive (see Table 2). The reduced commodity/input price relation brings about a reduction in mineral fertilizer and pesticide use. As a consequence of the more extensive production, the quantity of mineral nitrogen input decreases by more than 70% and that of pesticides by more than 90% compared with the scenario 'Going On' (compare black bars of the two scenarios in Figure 2). The crop rotation with potato is replaced by a crop rotation with soybean and faba bean. Sugar beet is grown without pesticide application. Its area is restricted by the sugar beet quota available. Sown meadow is grown in crop rotation with rape seed and grain maize, with exclusively organic fertilization and without the application of pesticides.

In the scenario 'More Ecology', reduced labour costs and increased prices for pesticides and mineral nitrogen give rise to production with low pesticide input and extensive input of mineral fertilizer (black bars of the scenario 'More Ecology' in Figure 2). This reduction leads to lower yields in compari-

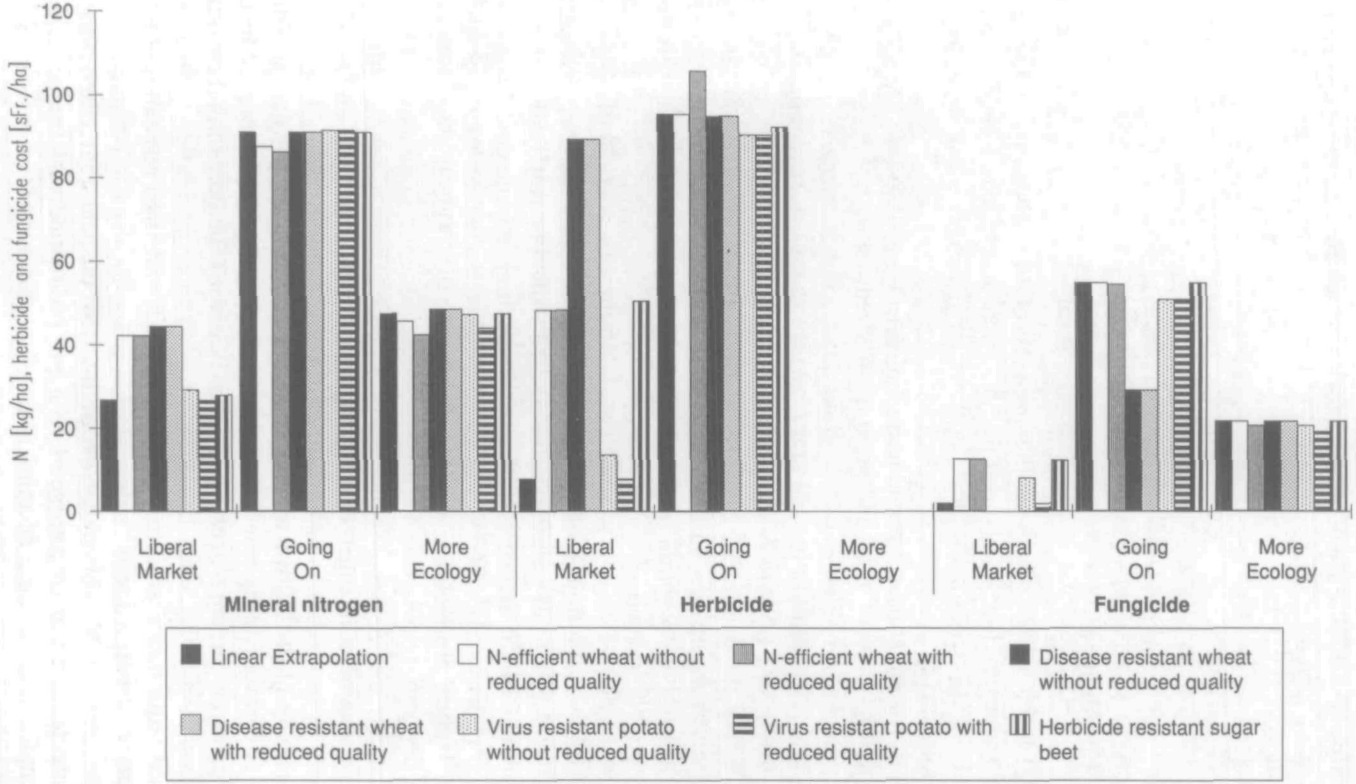

Figure 2. *Changes in mineral nitrogen input and herbicide and pesticide costs per hectare in the three scenarios due to the application of specific technological developments*

son with the scenario 'Going On' (e.g., of 7% for winter wheat and of 13% for potatoes). In addition, a greater number of crops are cultivated compared to the other scenarios. The cultivation of rape seed, soybean, winter barley and potato is expanded at the cost of grain maize and sown meadow (see Figure 3).

5.3. *Impacts of specific technological developments*

5.3.1. Introduction

In the LP model we evaluate the impacts of the following biological-technological developments on arable farming, developments which were assessed promisingly for the next 15 years by the experts participating in the Delphi survey:

a) Improved mineral nitrogen efficiency of wheat per dt grain yield
   - of 10% without yield and grain quality reduction,
   - of 25% with a diminution of grain quality but an increase in yield of 20%. The diminution of grain quality causes a reduction of the commodity price of 8.4%.

b) Improved resistance of wheat against leaf diseases
   - without a diminution of grain quality,
   - with a diminution of grain quality (which causes a reduction in the commodity price of 3.7%).

c) Virus resistance of potato which causes an increase in yield of 15%
   - without a diminution of tuber quality,
   - with a diminution of tuber quality (which causes a reduction of the commodity price of 10% for food potato).

d) Herbicide resistant sugar beet varieties which reduce herbicide and labour costs associated with the application of chemical weed control agents.

5.3.2. Economic competitiveness

With the help of the LP model, the economic competitiveness of particular new technologies can be assessed. Table 3 shows profits and losses of new technologies per ha compared to the situation with the corresponding old technology.

Wheat with an increased resistance to diseases and virus resistant potato varieties, both with reduced quality, are not economically competitive in the scenario 'Going On'. This can be explained by the fact that commodity prices are relatively high compared with pesticide prices; this makes new technologies which cause a decrease in quality in favour of better resistance uncompetitive.

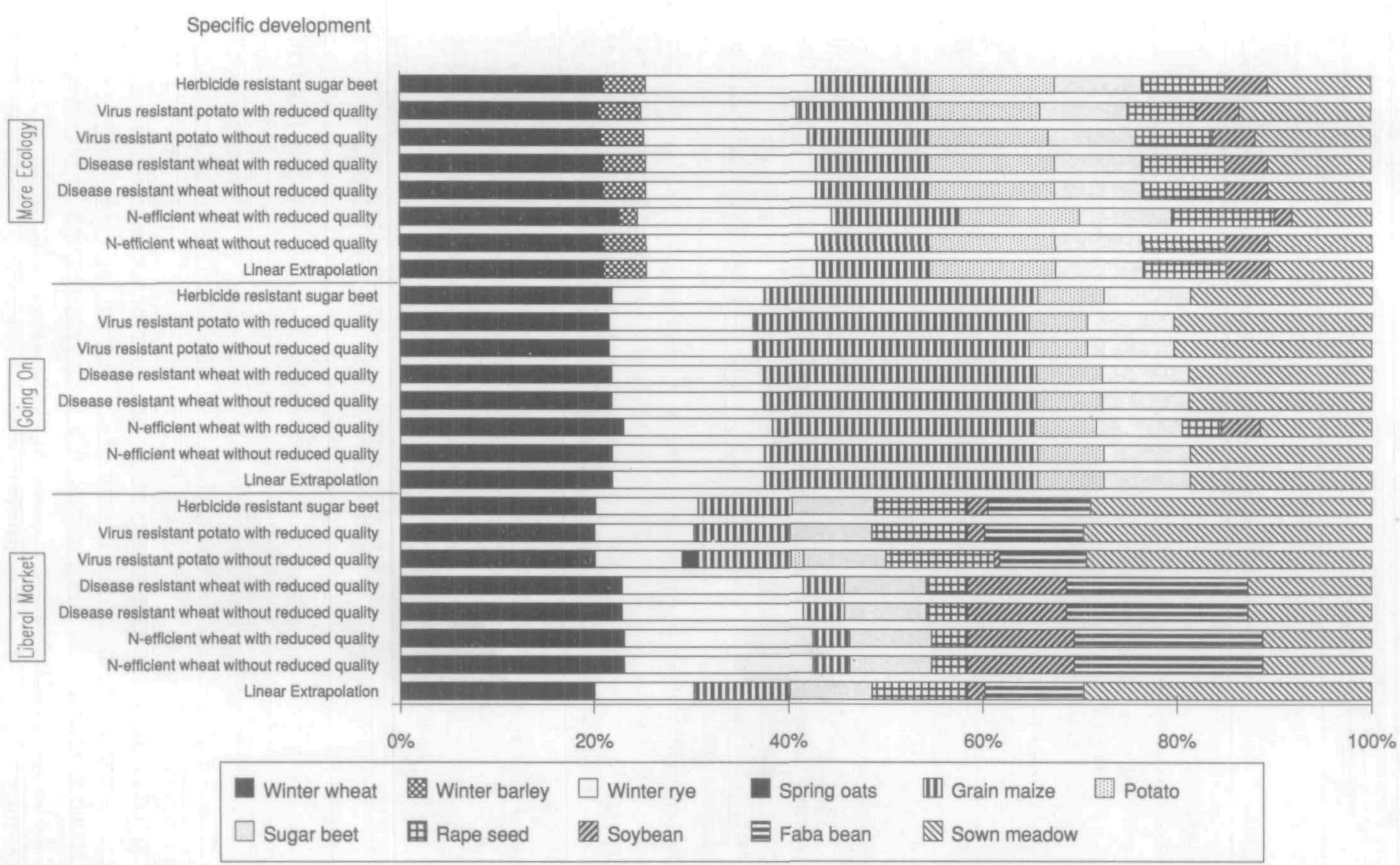

Figure 3. *Changes in cropping patterns in the three scenarios due to the application of specific technological developments*

Table 3. *Profits and losses of new technologies compared with the situation without the respective developments (sFr./ha)*

Technology	'Liberal Market'	'Going On'	'More Ecology'
Improved nitrogen efficiency of wheat			
–without quality and yield reduction	+11	+27	+48
–with quality reduction but increased yield	+323	+836	+790
Improved disease resistance of wheat			
–without quality reduction	+138	+145	+356
–with quality reduction	+49	−130	+88
Improved virus resistance of potato			
–without quality reduction	+147	+1,640	+1,576
–with quality reduction	0	−88	+146
Herbicide resistance of sugar beet	+30	+58	0

Wheat varieties with improved nitrogen efficiency are economically competitive in all three scenarios, especially in the case of wheat with quality reduction and increased yield. This high competitiveness is not due to the improved nitrogen efficiency but rather to a simultaneous increase in yield of 20%. This type of wheat corresponds to a high yielding variety with low baking quality.

Potato with improved virus resistance and without a diminution of tuber quality is competitive in the scenario 'Liberal Market'. If an improved virus resistance in potatoes causes a diminution of tuber quality, potato production is not competitive in this scenario.

In the scenario 'More Ecology' there is no impact of herbicide resistant sugar beet on the economic result because sugar beet is already grown without herbicide.

5.3.3. Impacts on optimal land use

This section discusses important effects of the evaluated technologies on land use.

The impact of N-efficient wheat with reduced quality is presented in Figure 3 (third line of the respective scenario). In the scenario 'Going On', sown meadow and grain maize is partially replaced by a crop rotation with rape seed and soybean. In comparison with the reference situation, wheat area is increased by about 5% and total wheat production by about 25%. Such an increase in production in a situation of saturated commodity markets would most probably cause a reduction in commodity prices (whether guaranteed or free market). A similar reaction can be observed in the scenario 'Liberal Market' (reduction of grain maize, rape seed and sown meadow in favour of a crop rotation with labour extensive crops such as soybean, faba bean and winter rye). The most striking fact in the scenario 'More Ecology' is the considerable reduction of soybean, winter barley and sown meadow in favour of wheat, rape seed and winter rye.

In all three scenarios, improved resistance of wheat against leaf diseases has the same effect on the optimal combination of crop rotations both with and without a diminution of quality (compare the fourth and fifth line of the respective scenario). An important impact on land use compared to the situation without the respective technology (linear extrapolation) can be observed only in the scenario 'Liberal Market'. The effect is very similar to that of N-efficient wheat (see above).

Virus resistant potato without a diminution of tuber quality is competitive in the scenario 'Liberal Market' (see Figure 3). A little over 1% of the land available in the model is grown with potato in a crop rotation with winter wheat, spring oats and rape seed. In the other two scenarios, the impact of increased yield due to virus resistance can be noted; the potato-grown area decreases by 5% to 12% but total potato production increases by 1% to 9%. The reduction of potato area is compensated for by grain maize and sown meadow.

The impacts of herbicide resistant sugar beet on land use are either marginal or non-existent (scenario 'Liberal Market').

5.3.4. Impacts on fertilizer and pesticide input

Figure 2 presents the differences in average mineral nitrogen and pesticide input caused by specific biological-technological developments compared to a situation without the respective development (linear extrapolation). All the pesticide prices are adapted to the price level of the scenario 'Going On', thus allowing easy comparison between the different scenarios.

It becomes obvious that the impact of the scenarios on fertilizer and pesticide input is much more important than that of technological progress. In the scenarios 'Liberal Market' and 'More Ecology', the tested technologies have a negligible impact on the already low levels of mineral fertilizer and pesticide input.

In the scenario 'Going On' there is a considerable reduction in yield-increasing production inputs (i.e., fertilizer, pesticides) only in the case of wheat varieties with an improved resistance to diseases. In the scenario 'Liberal Market' there is even an increased total input of these factors in certain cases, although it deals with input-saving technologies. For instance, the increased average mineral nitrogen input in the case of wheat – wheat with improved nitrogen efficiency – is due to the reduction of the crop rotation with organic fertilization exclusively in favour of a crop rotation with mixed mineral/organic fertilization.

Increased mineral nitrogen and herbicide input by wheat varieties with improved disease resistance in the scenario 'Liberal Market' can be explained in the following way: the reduction in fungicide requirement in wheat makes production methods with mineral fertilizer and pesticide application competitive in the crop rotation with sugar beet due to the reduced labour requirements (no more time is required to spray fungicides) and eliminated fungicide costs. The area of the crop rotation with soybean (mixed fertilization and pesticide application) increases at the cost of the one with sown meadow produced without pesticides and organic fertilizer. Fungicide applications are stopped (there are no more crops which require fungicide application), but herbicide input is increased ten times, and mineral nitrogen input is increased by about two thirds!

In comparing the optimizations of the 'Liberal Market' scenario with and without the inclusion of herbicide resistant sugar beet, the most important impact is a change from a production method without pesticide application to one with pesticide application in the crop rotation with sugar beet. The reduction in pesticide and labour cost of herbicide resistant sugar beet makes the use of pesticides competitive compared to the higher labour input of mechanical weed control, which was advantageous with the old technology. The result is a more than five fold increase in the herbicide input in this scenario!

5.3.5. Impacts on labour input

Change in labour input is one factor which explains differences in the economic competitiveness of the analysed biological-technological progress in the model. Table 4 presents these differences when they are bigger than 5% compared to the situation without the respective development (linear extrapolation).

The model results show that labour input is influenced by the following factors:

1. Total labour input depends on labour prices (the scenario) and the crops for which biological-technological progress is available (some crops intrinsically requiring more/less labour in cultivation).
2. If the application of new technologies causes a more constant distribution of total labour between different labour periods, then input of permanent labour is increased at the cost of occasional labour. Additional labour requirements in one labour period or in several labour periods because of changes in the optimal combination of crop rotations (due to the use of economically competitive new technologies) are covered by occasional labour.
3. In the model, a prospering economy is represented by higher opportunity costs for permanent labour (highest in the scenario 'Liberal Market', lowest in the scenario 'More Ecology'). Higher opportunity costs cause a more constant labour input at low level during the growing season. Labour peaks are then covered by occasional labour. This is illustrated by the results in Table 4. The increase in permanent labour input and the decrease in occasional labour input in the scenario 'Liberal Market'

Table 4. *Impacts of specific developments on labour input (relative differences compared to the situation without the respective development)*

Scenario	Specific development	Permanent labour (%)	Occasional labour (%)
'Liberal Market'	N-efficient wheat without reduced quality	+22	−55
	N-efficient wheat with reduced quality	+22	−55
	Disease resistant wheat without reduced quality	+21	−55
	Disease resistant wheat with reduced quality	+21	−55
	Virus resistant potato without reduced quality	+2	+8
'Going On'	N-efficient wheat with reduced quality	−15	+4
'More Ecology'	Virus resistant potato without reduced quality	+40	−16
	Virus resistant potato with reduced quality	+5	−6

owing to the cultivation of wheat with better N-efficiency and wheat with increased disease resistance can be explained by changes in optimal land use (see Figure 3): soybean cultivation is expanded at the cost of sown meadow. This reduces the labour peaks in spring and summer (normally associated with corn sowing and haymaking) which had existed without the application of this new technology and which had been covered by occasional labour. In the scenario 'Going On', the cultivation of N-efficient wheat with reduced quality has exactly the opposite effect: changes in land use pattern from labour intensive sown meadow to labour extensive soybean bring about a decrease in total labour requirements. New labour peaks during harvest time in summer are covered by occasional labour.

6. Conclusions

With some exceptions (e.g., herbicide and virus resistant crops), genetic engineering in plant production will be of importance for practical farming only in the long-range (20–30 years). Over such a long time span technological developments and their impacts are difficult to forecast more precisely.

In the medium-term (10 to 15 years), biological-technological progress can be expected that will allow a continuous increase in yield due to traditional methods of crop improvement (e.g., conventional plant breeding) as well as by means of biotechnology (e.g., *in-vitro* selection and propagation). Moreover, some special breakthroughs can be expected, such as the development of crops with improved virus or disease resistance.

Technologies which cause an increase in yield (e.g., virus resistant potato) are more competitive than those which only cause a reduction in pesticide or mineral fertilizer input (e.g., wheat varieties with reduced mineral nitrogen fertilizer requirements without yield increase). In scenarios where low input of pesticides and mineral fertilizer are already being practised before the emergence of a new technology with reduced requirements of these factors, the new technology has little impact on fertilizer and pesticide input. The future input level of mineral fertilizer and pesticides will be influenced more by the commodity–factor–price ratio than by factor saving biological-technological progress.

The use of economically competitive biological-technological developments by farmers does not result in any case in an increase in permanent labour demands in agriculture. A positive impact only exists if the application of the new technology causes a production programme with a reduction in labour peaks in favour of a better distribution of labour over the whole season.

The impacts of new technologies depend very much on the economic, social and political framework. In scenarios with high labour costs, new technologies have a stronger impact than in a scenario with low labour costs. Therefore, agricultural policy measures to control the application of biological-technological progress must be of top priority. Different product price – factor price ratios, subsidies and price increases, respectively, for production factors influence the use of new technology and can direct biological-technological progress positively. To obtain the different objectives of today's agricultural policy, such as sustainable and ecologically compatible production, economic competitiveness and maintenance of agricultural jobs require sophisticated political measures.

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